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DESIGN AND TEST OF AN NLF WING GLOVE FOR THE VARIABLE-SWEEP TRANSITION FLIGHT EXPERIMENT

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VSTFE GLOVE TEST AND REDESIGN

The Applied Aerodynamics Group has been involved in design efforts supporting the F-14 Variable-Sweep Transition Flight Experiment (VSTFE). The VSTFE was formulated between NASA Ames-Dryden and NASA Langley Research Center to establish a data base on the effects of the interaction between cross flow (CF) and Tollmien-Schlichting (TS) instabilities on boundary-layer transition utilizing the F-14 aircraft as a test bed. The design effort involved modifying the F-14 wing outer-panel such that favorable pressure gradients could be generated over a wide range of flight conditions.

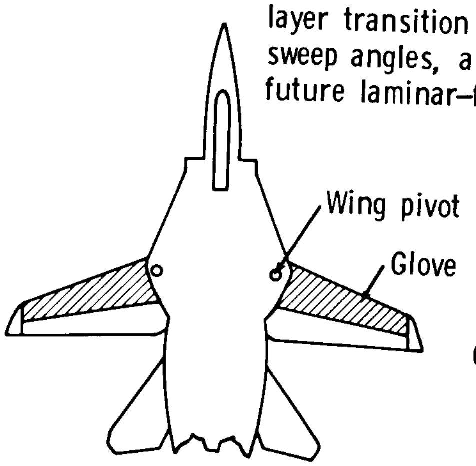
Background information relating to the initial computational glove design will be presented. The initial design relied extensively on both two- and three-dimensional transonic analysis methods applied in a "cut-and-try" manner. The initial design was tested in the National Transonic Facility (NTF) along with the baseline F-14 to verify the glove design and to obtain data supporting safety of flight issues. Based on the pressure data available from the NTF test a decision was made to redesign the inboard region of the glove to increase the envelope over which usable flight data could be obtained. The redesign process and two- and three-dimensional results from the redesign effort will be presented. Finally, a summary of the design and test results to date will be presented along with the status of the flight experiment.

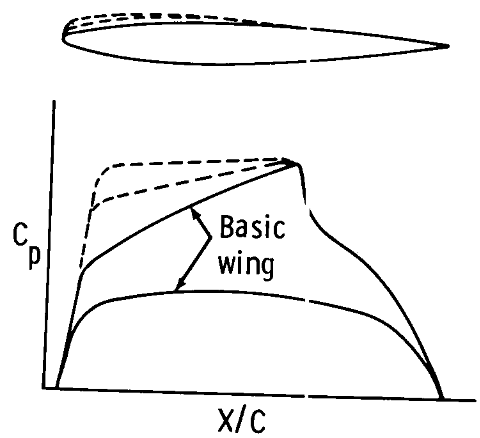
* BACKGROUND
* NTF TEST RESULTS
* REDESIGN PROCESS
* RESULTS FROM REDESIGN EFFORT
* SUMMARY AND STATUS

F-14 VARIABLE SWEEP FLIGHT EXPERIMENT

An important question that must be answered in order to design wings which effectively utilize NLF relates to boundary-layer transition. It is known that for boundary layers in a three-dimensional flow environment, there is an interaction between cross flow (CF) and Tollmien-Schlichting (TS) instabilities that can cause transition to occur in an otherwise favorable environment (i.e., favorable pressure gradient, smooth surface, etc.), Hanks, 1984. In order to assist in identifying and quantifying the influence of the CF-TS interaction on wing-boundary-layer transition, data are needed for various combinations of favorable pressure gradients, Reynolds numbers, and sweep angles. This is the objective of the VSTFE. The F-14 aircraft was selected as the test bed aircraft because of its variable sweep capability, which would allow data to be taken over a wide range of sweep angles.

Objective: Obtain accurate in-flight measurement of boundary-layer transition location for wing pressure distributions, sweep angles, and flight conditions representative of future laminar-flow transport aircraft.

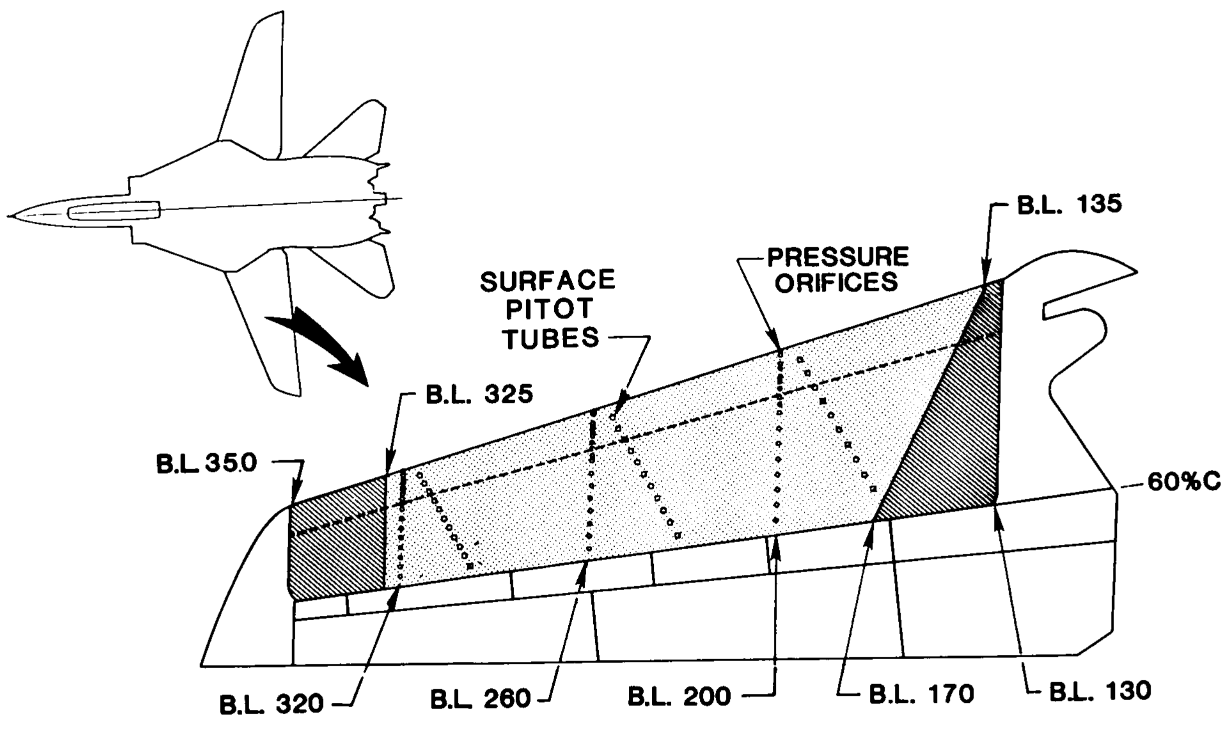




APPROACH

The approach of this flight experiment is to modify the wing outer panel by gloving on a foam and fiberglass contour so that favorable pressure gradients will be generated over a range of Mach numbers, sweep angles, and Reynolds numbers. Two different gloves were designed which correspond to an M = 0.70 and M = 0.80 design condition. NASA Langley was responsible for the M = 0.70 glove design, and Boeing Aircraft Company was responsible for the M = 0.80 glove design. Both gloves were to be flown simultaneously, one on each wing of the F-14, resulting in an asymmetric configuration. Hence, a maximum constraint on the rolling moment because of the asymmetric configuration was imposed on the design.

Glove Layout



PROJECT PLAN

The project can be considered to consist of four phases: flight test of the "clean-up" glove, design of M = 0.7 and M = 0.8 gloves, wind tunnel testing of baseline and glove configuration, and flight test of the glove configuration. The "clean-up" glove corresponds to the contours of the basic F-14 wing. It was built up of foam and fiberglass and installed on the outer panel to demonstrate that acceptable tolerances could be maintained in the fabrication process and to obtain pressure and boundary-layer measurements in the flight environment.

Concurrent with the "clean-up" glove flight tests, two gloves were designed for M = 0.7 and M = 0.8 design points. The gloves were designed such that a neutral to slightly favorable pressure gradient was generated on the glove upper surface at the maximum test altitude, 35,000 feet, for 1 "g" flight conditions. This allowed more favorable gradients to be obtained for 1 "g" conditions at lower altitudes.

The designs and the baseline F-14 configuration were then to be tested in the NTF. The test would allow a verification of the designs and determination of changes in the performance and flying qualities of the modified configuration relative to the baseline F-14. Additionally, if any adverse effects were discovered during the data analysis, time would be available to modify the designs before the VSTFE configuration was to be flight tested.

Initially, both gloves were to be flight tested simultaneously on the F-14. However, the availability of the test-bed aircraft precluded the modification of both wing panels and completion of the flight test program. Based on the computational analysis and wind tunnel pressure data available for each of the designs, a decision was made to limit the flight test to the M = 0.7 design.

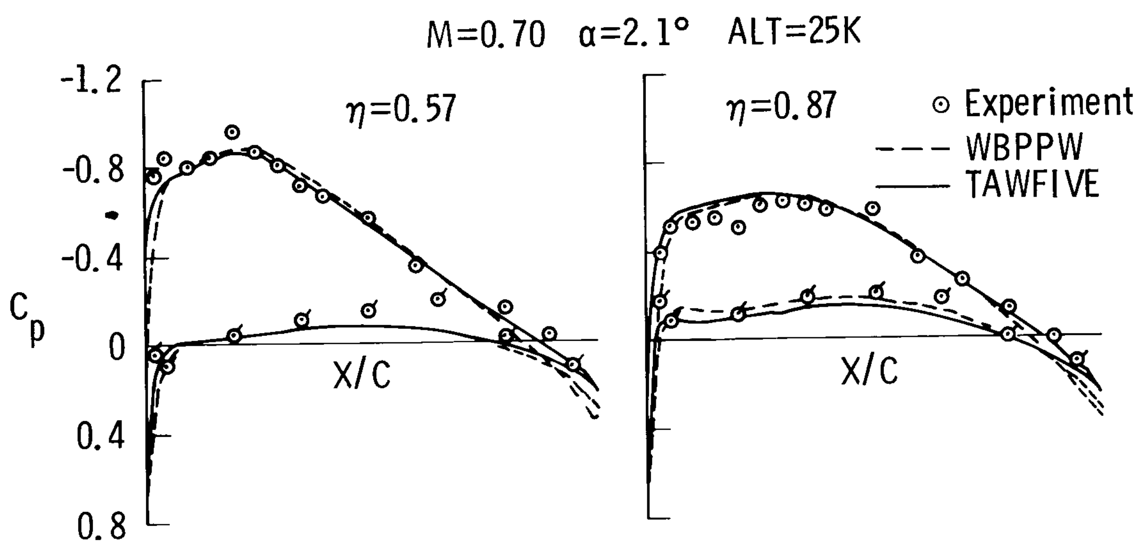
The final phase of the program is to install the glove design on the wing panel, perform the flight testing, and analyze the data. This is the only phase remaining to be completed.

* Fly "Clean-up" Glove
* Design gloves for M=0.7 and M=0.8 design points
* Conduct wind tunnel test on baseline and modified configurations
* Fly modified configuration

COMPARISON OF FLIGHT TEST AND COMPUTATIONS

A flight test of the F-14 was conducted to explore the test envelope for the VSTFE and to obtain wing pressure data on the basic aircraft (Moes and Meyer, 1985). From these data, four flight points were designated to be of primary interest. Three of the points correspond to corners of the flight envelope for the VSTFE, and the remaining point is an intermediate flight condition.

Analyses were made in the WBPPW (Boppe and Stern, 1980) and TAWFIVE (Melson and Streett, 1983) codes at the flight Mach number and measured angle of attack (Waggoner, et al., 1985). Overall, the comparisons are quite good. Several observations need to be made concerning the comparisons. First, the flight data showed a flow expansion at the leading edge followed by a compression that neither code predicted. This indicated that possibly the leading-edge slat deflected under load. Static loading corresponding to flight loads confirmed this. The differences seen in leading-edge expansions between the two codes are consistent with the code formulations. Shock resolution is much better in the WBPPW code results because of the denser grid in that region as compared to the TAWFIVE code. Additionally, the TAWFIVE code uses conservative differencing where WBPPW uses nonconservative differencing, which accounts for the discrepancy in shock location.



DESIGN CONSTRAINTS

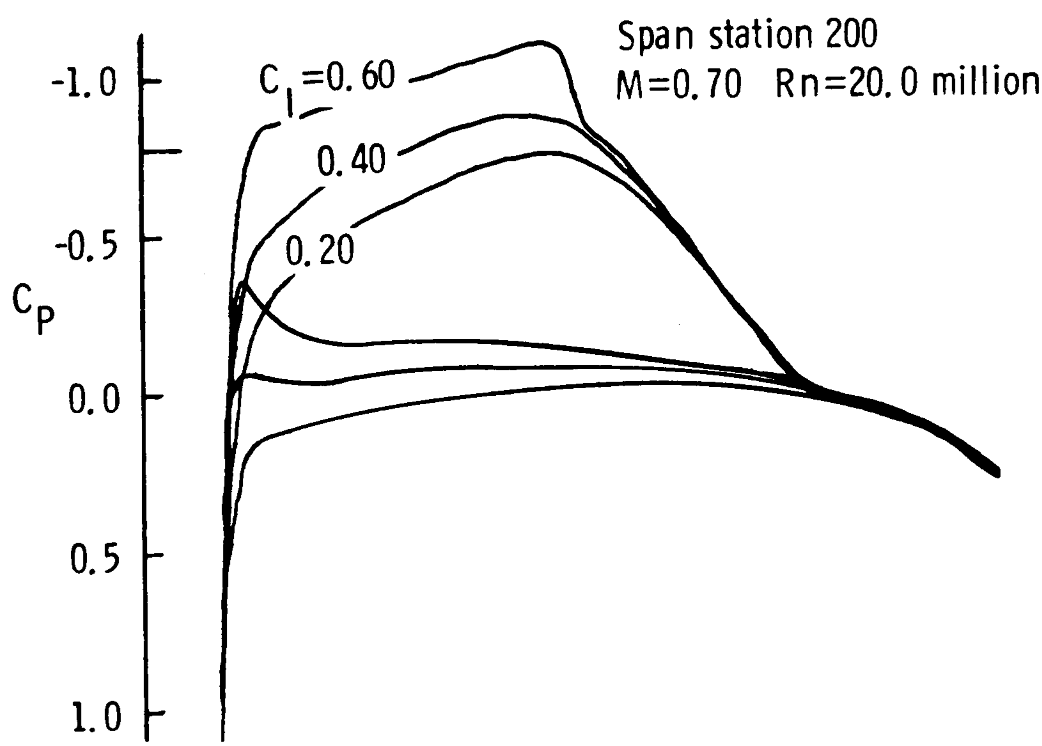
The physical constraints on the modifications evolved with the design program. The final constraints and supporting rationale are as follows:

* The upper surface could be modified from the leading edge to the spoiler hinge line ($x/c = 0.60$) since the spoilers are used for low-speed roll control. Modifications on the lower surface were limited to the first 10-percent chord because of the glove fabrication method.
* The thickness of the glove at the spoiler hinge line must be less than 1.0 inch. This constraint was imposed to ensure spoiler effectiveness. For reference, the wing mean chord is 105.66 inches.
* The thickness of the glove was required to be a minimum of 0.65 inches. This constraint was required to minimize the possibility of the leading-edge slat deflecting under load.
* The rolling moment resulting from the asymmetric configuration was required to be less than 0.01 over the flight test envelope. This level of rolling moment could be counteracted by tail deflection, allowing the spoilers to remain undeflected during the test portions of the flight.

- Upper surface modification
  $0.0 \leq x/c \leq 0.60$
- Lower surface modification
  $0.0 \leq x/c \leq 0.10$
- Increment at spoiler hinge line less than 1.0 inch
- Increment over glove region a minimum of 0.65 inches
- Differential rolling moment less than 0.01

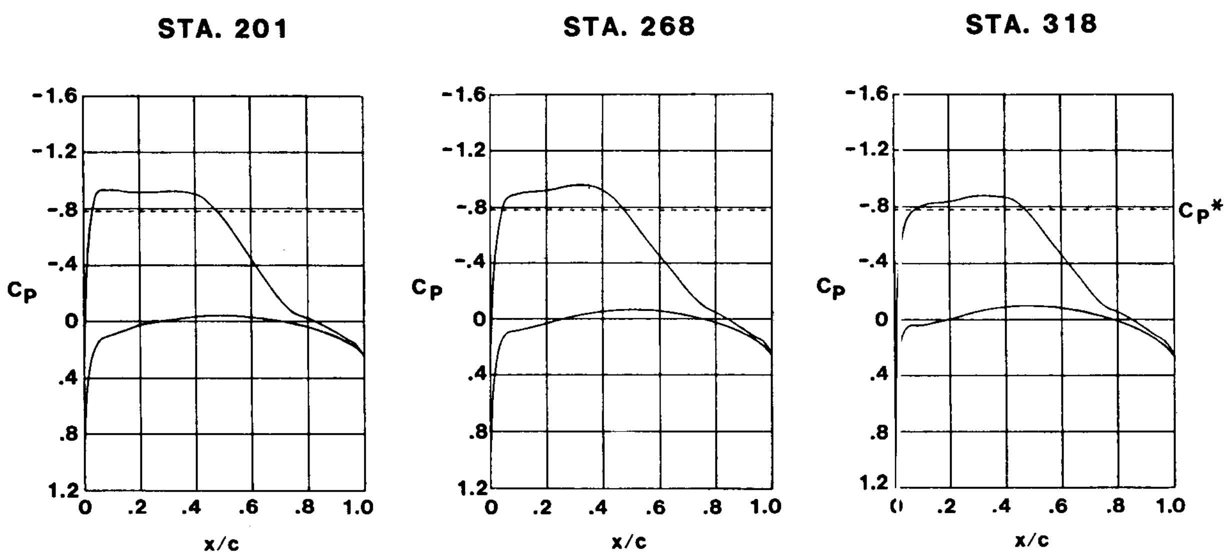
DESIGN AIRFOIL MEETING FINAL CONSTRAINTS

The design point selected corresponded to a "worst case" condition for the targeted Mach number (M = 0.70). This condition corresponded to the highest altitude, hence the largest lift coefficient for 1-g flight. If the sectional contours could be modified such that a slightly favorable gradient could be generated from the leading edge to the midchord region at this condition, then at lower altitudes there would be an even more favorable pressure gradient. Five defining stations were chosen to be recontoured using linear lofting between defining stations. These stations corresponded to the inboard and outboard extent of the glove and three intermediate defining stations. With two-dimensional analysis and design procedures, upper surface contours were defined which met the aerodynamic and physical constraints for each defining station. A favorable pressure gradient was observed from the leading edge to about midchord over a range of lift coefficients on the design airfoil.



THREE-DIMENSIONAL ANALYSIS OF GLOVE DESIGN

Final computational verification of the design was realized by analyzing the entire configuration (fuselage, nacelles, strake, and outer panel) in the TAWFIVE code. Results show that the design objectives were met over the range of lift coefficients corresponding to the altitudes of interest at M = 0.70. Presented below are the results for the high altitude case at the design Mach number. The results show a neutral pressure gradient on the upper surface at the most inboard span station and slightly favorable pressure gradients at the two outboard span stations.

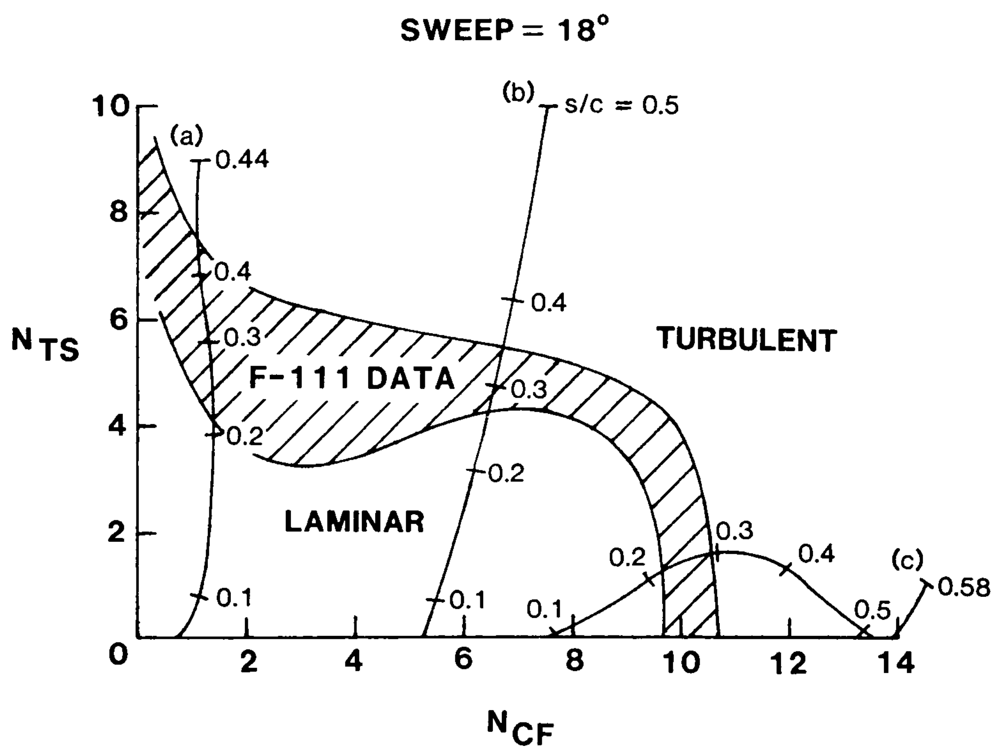


CALCULATED N-FACTORS FOR THE ORIGINAL GLOVE DESIGN

Boundary-layer disturbance growth was analyzed using the method of Mack, 1979. The M = 0.7 glove design was analyzed at three conditions to assess its operating range and usefulness in obtaining transition data (Rozendaal, 1986). The conditions were:

a. Level flight, M = 0.7, 25,000 feet
b. Level flight, M = 0.7, 35,000 feet
c. Level flight, M = 0.8, 35,000 feet

The data show that for the three conditions a wide variation in CF and TS N-factors is available. Near its design point the glove shows a predominance of TS growth at low CF N-factors. At lower altitudes at the design Mach number, the glove produces moderate growth in the CF instability mode and rapid growth in the TS mode. At M = 0.8, the instability growth is most noticeable in the CF mode. These data indicate the range of instability interactions available from the M = 0.7 glove design pressure distributions.



NTF WIND TUNNEL TEST

After the designs were completed, the glove designs and the F-14 baseline configuration were tested in the NTF. There were two primary objectives for the test entry. The first was to determine the incremental changes in the performance and flying qualities of the VSTFE configuration relative to the baseline. This involved comparing performance and stability and control data on each configuration over the anticipated flight test envelope. Two areas of significant interest were the levels of rolling moment generated on the asymmetric VSTFE gloved configuration and maximum lift generated at approach speeds. Analysis of the data indicated that the increments between the two configurations were minimal.

The second objective was to verify the computational designs. The glove designs had pressures available at locations corresponding to the flight test instrumentation. The experimental pressures could be compared to the computational predictions at these locations. Any discrepancies between the computed and experimental pressures could then be assessed and resolved if necessary.

OBJECTIVES:

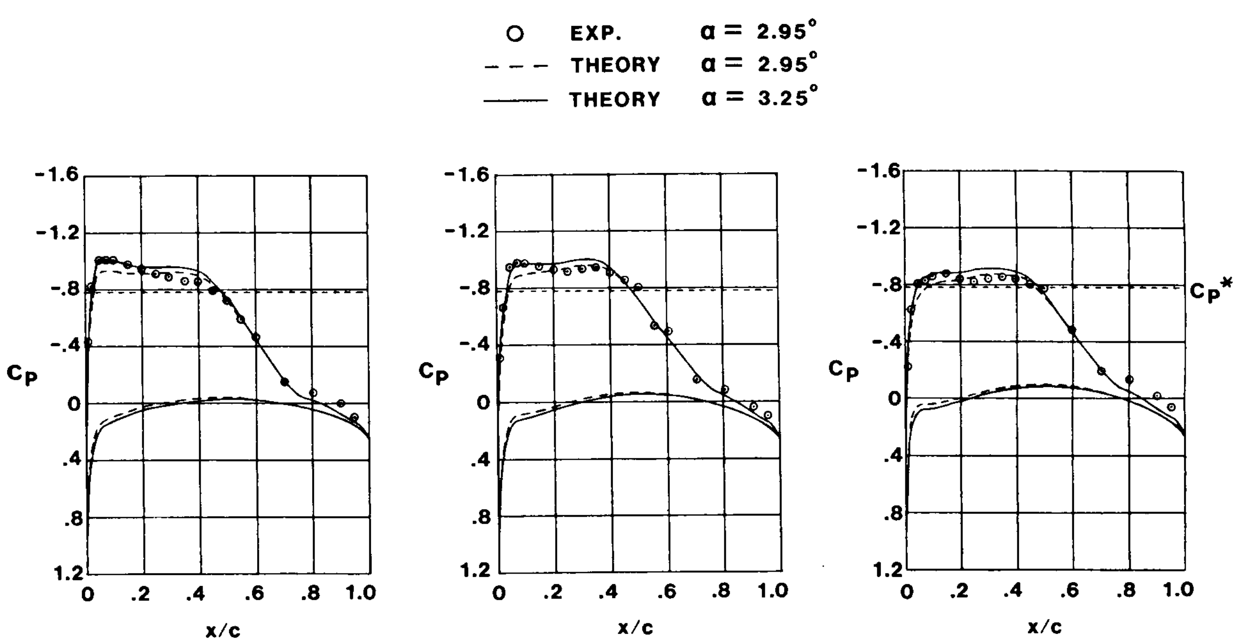
* SAFETY OF FLIGHT—INCREMENTAL CHANGES
  * Performance
  * Stability and Control
  * Rolling Moment
  * $C_{L_{MAX}}$ at Approach Speeds
* VERIFICATION OF COMPUTATIONAL PREDICTIONS

ENVELOPE:

* $M = 0.2 — 0.9$
* $\Lambda_{LE} = 20° — 35°$

COMPARISON OF THEORETICAL AND EXPERIMENTAL PRESSURE DISTRIBUTIONS AT M = 0.7

Experimental wing pressure distributions for the original glove are compared with theoretical results from the TAWFIVE 3-D transonic code in the figure below. The Mach number of 0.7 and angle of attack of 2.95 degrees represent the high-altitude, level-flight design condition for the flight experiment. The analysis code was first run matching the experimental angle of attack. While the overall correlation was good, the suction peak and the slight adverse pressure gradient that occur near the leading edge in the experimental data were not predicted. Often in comparing potential flow calculations with experimental data it is found that the codes underpredict the lift levels and must be run at an angle of attack slightly higher than the experiment to achieve good correlation. Therefore, additional calculations were made with the angle of attack increased to 3.25 degrees. These results more closely matched the experimental pressure levels and gradients near the leading edge, so this angle of attack was chose for any further analytical or design work. It is interesting to note that the theory and experiment matched fairly well aft of 58 percent chord where the glove ended abruptly in an aft-facing step on the wind tunnel model, but was smoothly faired into the basic wing for the computations.

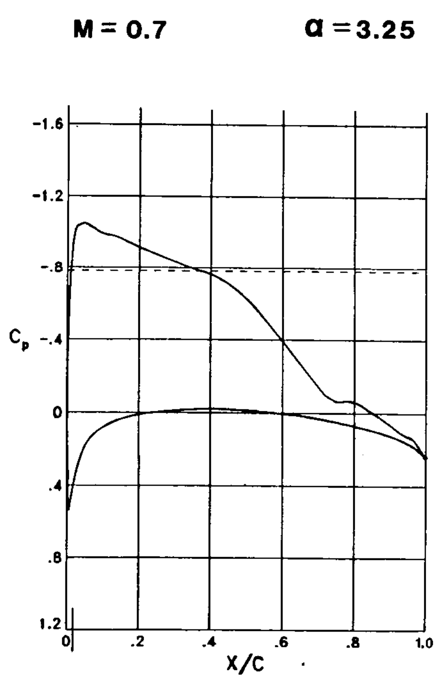


STA. 201 STA. 268 STA. 318

THEORETICAL PRESSURE DISTRIBUTION AT STATION 134

The original plan for instrumentation on the glove had pressure orifice rows located at span stations 200, 260, and 320. It was decided that an additional row of orifices should be installed at station 160 to take advantage of the larger chord (and thus larger Reynolds numbers) in this region as well as to provide a more complete description of the glove pressures. The experimental pressure data indicated that the upper surface pressure distributions at the inboard stations were slightly more adverse than the relatively flat distributions of the outboard stations due to the increased upwash from the strake. If this trend continued for the stations inboard of 200, the original glove design would probably not allow any significant transition location data to be obtained in this region. Since the wind tunnel model did not have any instrumentation in this area of the glove, computational results were used to evaluate this concern.

The calculated pressure distribution for station 134 near the inboard edge of the glove is shown in the figure below. A fairly strong leading-edge peak is present, and the following adverse gradient would probably cause the laminar flow to undergo transition to turbulent flow very rapidly. Since early transition at this station could contaminate the flow at station 160, a redesign effort for the inboard portion of the glove was initiated.



INBOARD GLOVE REGION MODIFICATION

Based on the NTF test results and the good correlation of the theoretical and experimental data, it was felt that some very useful data could be obtained on the inboard portion of the glove if the original design constraints were relaxed to allow some additional design work. The objective of the new design was to eliminate the adverse gradient over the inboard part of the glove so that the entire upper surface of the glove would have a favorable-to-neutral pressure gradient in the leading-edge region at the high altitude, M = 0.7 design point. Since there would not be an opportunity to verify a new design in the wind tunnel due to time constraints, it was decided to modify only the region of the glove inboard of station 200.

In order to reduce the leading-edge pressure peak, the leading edge of the glove had to be drooped for better alignment into the oncoming flow. This necessitated relaxing several of the design constraints in this region. The glove overhang region was extended to 4 inches ahead of the basic wing leading edge and the minimum allowable glove thickness was reduced to 0.25 inches to enable the drooped sections to fit over the existing wing. The match point for the glove to fair into the lower surface was also extended to 30 percent chord to minimize any concavity that might occur.

OBJECTIVE:

* Remove adverse pressure gradient in leading edge region over entire glove at high altitude, M = 0.7 design point

CONSTRAINTS:

* Minimal change to tested geometry
* Overhang region extended to 4 inches
* Minimum thickness relaxed to 0.25 inch inboard of span station 200
* Lower surface modification extended to 30% chord

REDESIGN PROCESS

The redesign of the inboard glove region utilized a three-step approach. The first stage was a parametric study of leading-edge camber or droop distributions, using the NYU airfoil code (Bauer, et al., 1975) to calculate the pressure distributions. From this study, airfoils having favorable gradients in the leading-edge region with as little disturbance as possible to the rest of the pressure distribution would be selected. The second step involved modifying these airfoils using an airfoil design code to obtain favorable upper surface pressure gradients extending from the leading edge to about midchord and to minimize lower surface leading edge pressure peaks caused by the droop. (The airfoil design code could not be used for the droop design since at that time it required a fixed leading edge point.) The final airfoils generated by the design code were then evaluated in the three-dimensional flow environment using the TAWFIVE code. This third step in the process included runs at conditions throughout the flight envelope as well as the design point.

* Parametric study to define leading-edge camber distribution

* Application of 2-D design code

* Evaluation with 3-D analysis code

PARAMETRIC STUDY OF CAMBER DISTRIBUTION

Incremental camber distributions were added to the leading-edge region of two airfoil sections from the inboard region of the glove. The camber distribution was generated using a polynomial equation similar to the camber equation for the NACA four-digit airfoils, but modified to produce leading-edge droop and no camber change at the match point. The magnitude of the droop was varied from one to four percent chord. Two types of polynomials were tried: quadratic, which matched the ordinate of the original camber line; and cubic, which matched both the ordinate and slope of the original camber line. The chordwise extent of the droop was also varied, up to a maximum value of 30 percent chord.

The results of this study indicated that the four percent droop cases gave too strong a pressure peak at the leading edge on the lower surface and just ahead of the match point on the upper surface. The one percent droop had small disturbances at these locations, but the upper surface favorable gradient was fairly weak and would probably become adverse in the three-dimensional flow case. The cubic polynomial camber airfoils had slightly smoother pressure distributions than the quadratic camber airfoils. The effect of increasing the chordwise extent of the droop was to strengthen the favorable gradient of the upper surface while reducing the pressure peak at the match point. Based on these results, the airfoils having the two percent cubic camber distribution extending over the first thirty percent of the chord were chosen for further modification by the airfoil design code.

* Maximum camber at leading edge (droop)
* Order of polynomial fit for camber distribution
* Chordwise extent of modification

Analysis of 3 x 2 x 3 Matrix

$\Downarrow$

Redesigned Camber Distribution

TWO-DIMENSIONAL DESIGN CODE

The airfoils chosen from the parametric camber study were further modified using an airfoil design code developed at NASA Langley. This code is based on the NYU analysis code (Bauer, et al., 1975) and modifies an airfoil contour to achieve a target pressure distribution. The design method begins by calculating the pressure distribution for the initial airfoil shape and comparing it to the target pressures. The airfoil shape is then modified based on the differences in these pressures using a design algorithm similar in concept to the ones used by Barger and Brooks (1974) and Davis (1979). This algorithm relates the difference in the predicted and target pressure coefficients to the surface curvature in subsonic and mildly supersonic flow regions. For regions with stronger supercritical flow (local Mach numbers greater than 1.15), a term that relates surface slopes to pressure coefficients is also included. The changes in surface slopes and curvatures are then used to modify the initial airfoil, and the resulting airfoil is analyzed by the NYU code. This predictor/corrector approach is repeated until the pressures and airfoil shape converge.

Target pressures for the design were defined in a three-step process. Analysis pressure distributions were obtained on the drooped airfoils. Next the undesirable flow expansion ahead of the droop match point (30-percent chord) on the upper surface was eliminated by reducing the maximum pressure coefficient near the leading edge. Finally, the strength of the favorable pressure gradient behind the match point was increased to help maintain airfoil thickness. The code required approximately 4 design cycles to achieve the target pressures.

* Based on Garabedian and Korn analysis code

* Modifies contour to achieve a specific pressure distribution

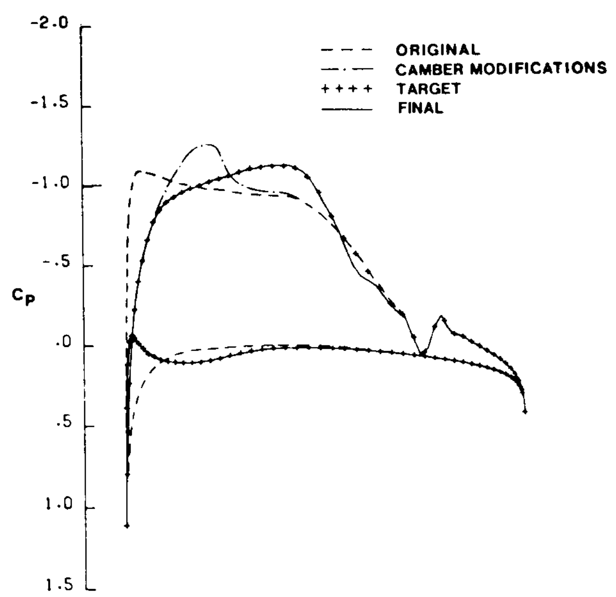
* Predictor/corrector design algorithm

    * Subsonic $-\Delta C_p = f(\text{surface curvature})$

    * Supersonic $-\Delta C_p = f(\text{surface curvature, surface slope})$

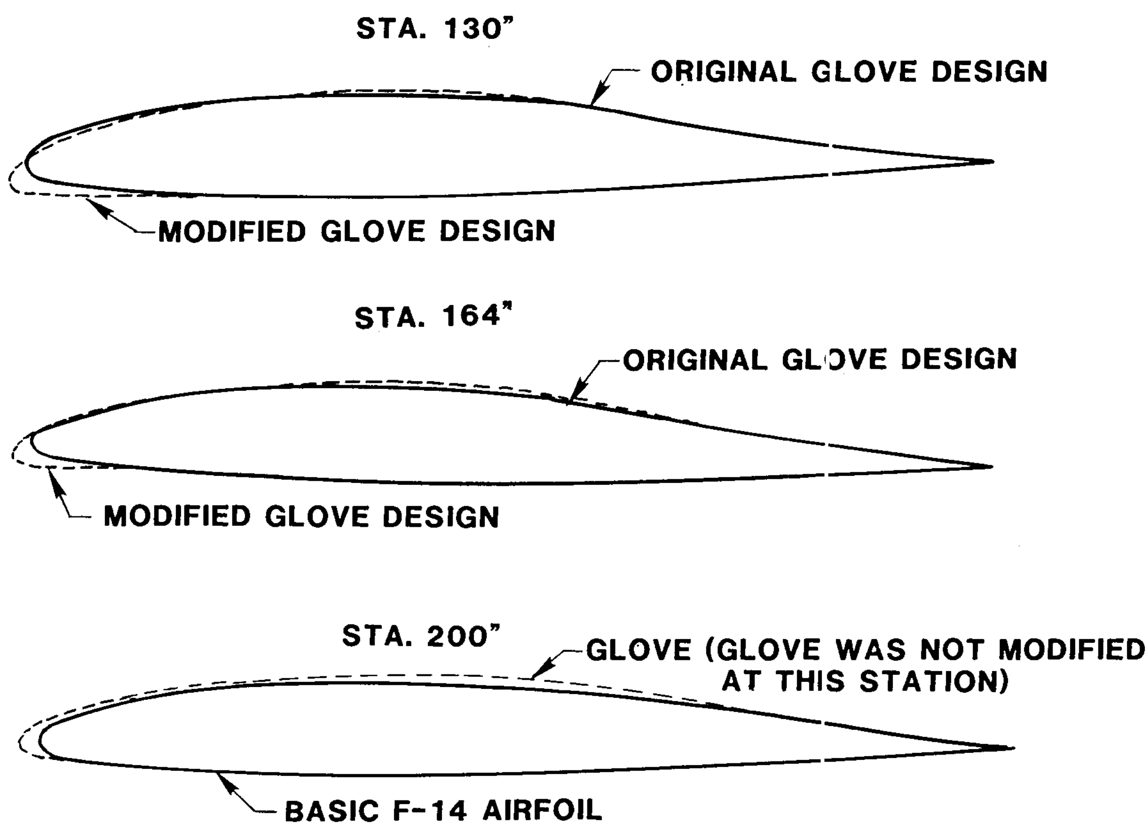
TWO-DIMENSIONAL PRESSURE DISTRIBUTIONS FOR GLOVE AIRFOIL AT STATION 130

Calculated two-dimensional pressure distributions are shown in the figure for the airfoil at station 130 at various stages of the design effort. The dashed line represents the pressure distribution for the original glove at two-dimensional conditions that are equivalent to the high altitude design point. The two-dimensional Mach number was calculated using simple sweep theory, and the angle of attack was adjusted to give a pressure distribution that closely matched the one from the three-dimensional code. The results for the airfoil from the camber study show that the leading-edge peak on the upper surface was eliminated, but a peak formed instead just ahead of the match point. This pressure distribution was modified to create the target pressures that were input into the airfoil design code. The final airfoil results (solid line) matched the targets everywhere except near sixty percent chord on the upper surface. This difference was caused by the constraint that the airfoil could only be modified ahead of sixty percent on the upper surface and thirty percent on the lower surface.



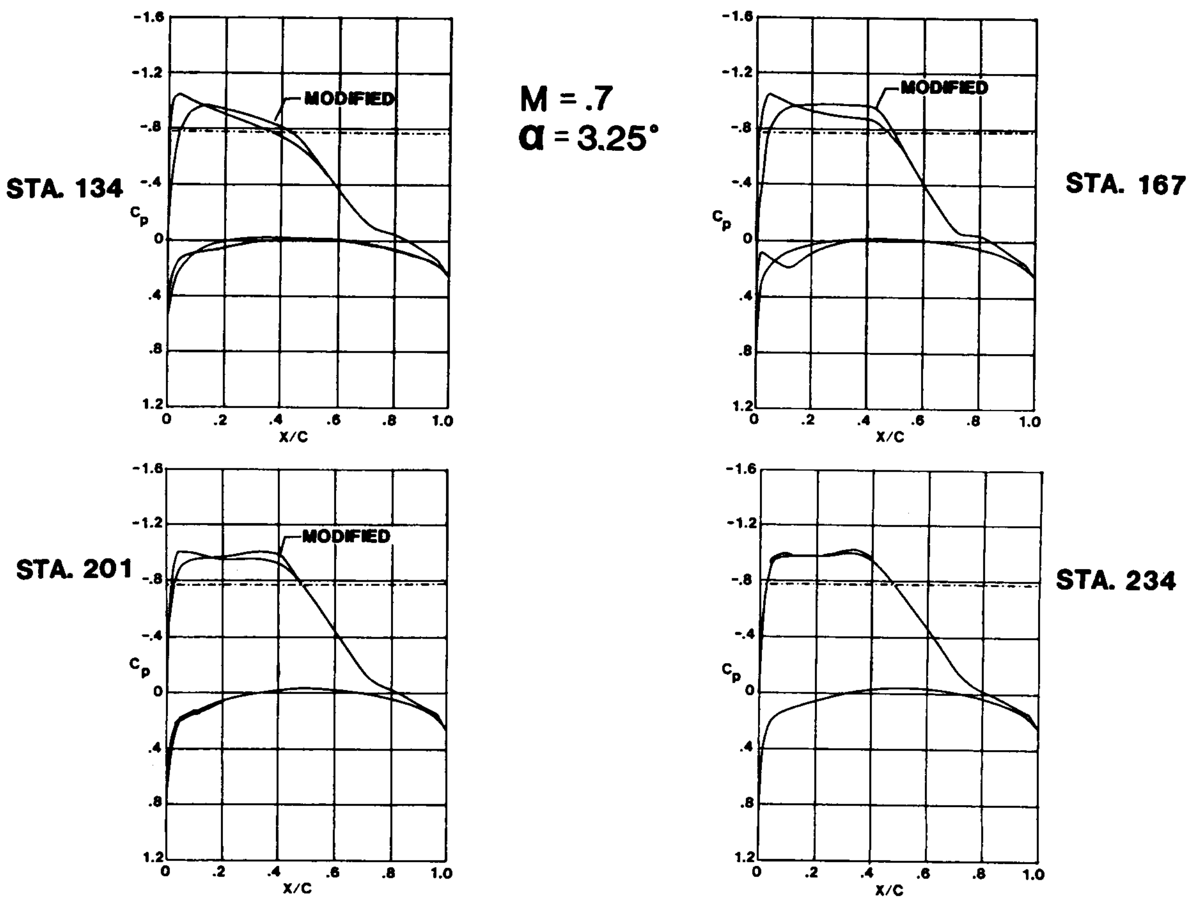
FINAL AIRFOILS

The final airfoils from the redesign process are shown in the figure. The drooped airfoils at stations 130 and 164 are overlaid on the original glove designs while the glove airfoil at station 200, which was not redesigned, is compared to the basic wing airfoil. The leading-edge extension and droop for the new gloves is evident, and the need to relax the minimum glove thickness can be seen at station 130, where the modified glove undercuts the original glove (though it is still outside the basic wing). The new glove sections have a slightly greater maximum thickness, but are still within the original constraint for the step size at the end of the glove on the upper surface.



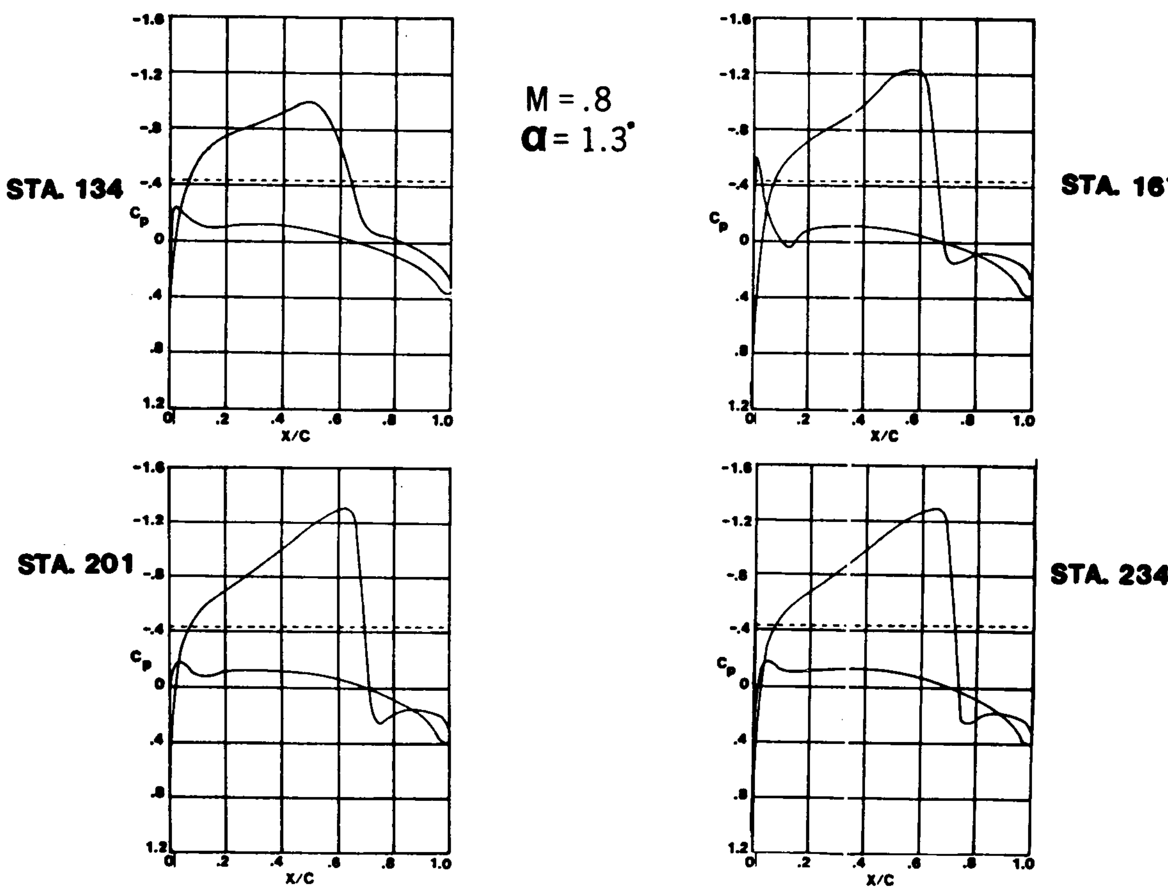
THREE-DIMENSIONAL ANALYSIS OF MODIFIED GLOVE - M = 0.7

Analysis of the modified glove design was performed at the design condition and other flight conditions throughout the flight envelope. Results are presented below for the M = 0.7, high altitude design point and compared against results from the original design. Note that at the most inboard station presented, span station 134, the adverse pressure gradient was reduced but not eliminated. However, the pressure peak was reduced at the leading edge on the upper surface. Moving outboard to station 167, note that the modified glove exhibits a neutral pressure gradient while the pressure expansion and slightly adverse gradient evident in the original design has been eliminated. The pressure distributions from the two designs are virtually indistinguishable from station 234 outboard. Hence, the modifications have allowed useful data to be obtained over a wider range of flight conditions than were available from the original glove design.



THREE-DIMENSIONAL ANALYSIS OF MODIFIED GLOVE - M = 0.8

The data presented in the figure below represent the pressure distributions at the worst case condition in the proposed flight envelope, level flight at M = 0.8 and 35,000 feet. The concern at this condition is related to the shock strength causing boundary-layer separation over the aft part of the wing. Although the shocks seem relatively strong at this condition, they are no stronger than the shocks on the baseline F-14 configuration at comparable conditions. No other adverse effects are observed in the inboard pressure distributions for the modified gloved configuration.



SUMMARY

Gloves for M = 0.7 and M = 0.8 design points have been computationally designed and analyzed at conditions over the proposed flight test envelope. The resulting computational pressure distributions have been analyzed in a boundary-layer stability code. These results indicate that the available pressure distributions offer a wide range of combinations of CF and TS N-factors.

The glove designs along with the baseline configuration were tested in an entry into the National Transonic Facility. Analysis of the force and moment data showed no significant differences in the performance and stability and control characteristics between the baseline and gloved configurations. The rolling moment constraint was met over the entire flight test envelope for the gloved configuration. In addition, there were only minor differences in the maximum lift coefficient at approach speeds for the two configurations.

Pressure distributions from the NTF test confirmed the design pressure distributions were achieved. However, it was decided that with minor modifications to the inboard region of the glove, useful available data could be significantly increased by adding another row of pressure orifices at span station 167. The inboard glove region was successfully redesigned, and the modified glove was analyzed over the proposed flight envelope.

- Initial gloves computationally designed
- NTF force and moment data showed no significant differences between baseline and VSTFE configurations
    - Performance
    - Stability and Control
    - Rolling Moment
    - $C_{L_{MAX}}$ at Approach Speeds
- Pressure distributions from NTF test confirmed target design
- Inboard glove region successfully redesigned

STATUS

The clean-up glove flight test has been completed and the data are being analyzed. The newly designed modified glove contour has been built up on the F-14 wing, and the wing has been reinstalled on the aircraft. Flight test instrumentation is now being checked out for the modified glove. Flight testing is scheduled to resume in late Spring of 1987.

* Clean-up glove flight test completed

* Modified glove contour has been installed on wing

* Flight test scheduled to resume May 1987

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